Institut de recherche en mathématique et physique
Centre de Cosmologie, Physique des Particules et Phénoménologie

Electroweak and Higgs phenomenology including EFT

Celine Degrande

Plan

- Electroweak interaction
  - Beta decay and Fermi theory
  - Parity violation
  - Weak algebra and neutral currents
  - Electroweak theory
- Spontaneous symmetry breaking
  - U(1)
  - SM
  - Fermions masses
- Effective field theory
  - Introduction
  - Non-interference and revival
  - CP example

Exercices in purple by hand and in MadGraph

Connection to pheno along the way

Questions

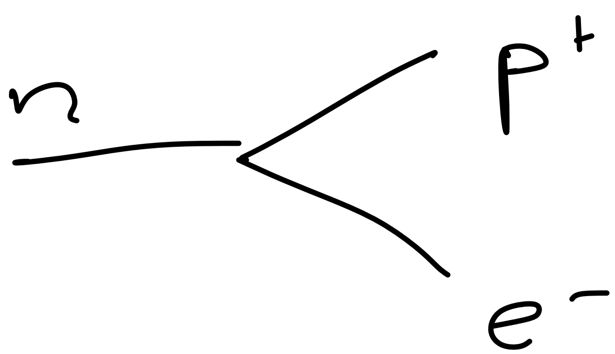
- Does the weak interaction explain why they are rocky planets?
- Is the proportionality of the Higgs to fermion couplings to their masses due to
  - Parity
  - Gauge invariance
  - Spontaneous symmetry breaking
- Why are they so many muons produced by CR in the atmosphere?

Questions

- Why is the proton stable and not the neutron?
- Why is neutrino detection due mainly to nuclear and not electrons?
- Can I predict the W and z masses from low energy data?

Electroweak interaction

Beta decay

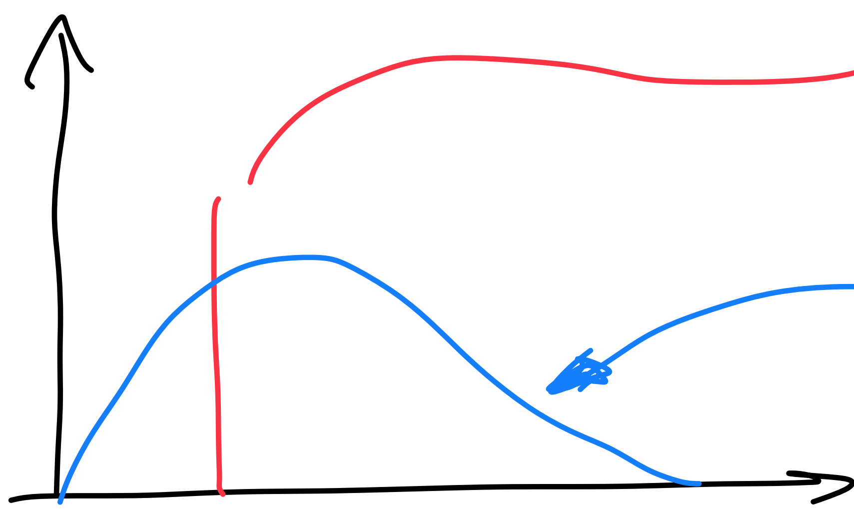


$1 \longrightarrow 2$

Ex: $p_n = p_p + p_e$

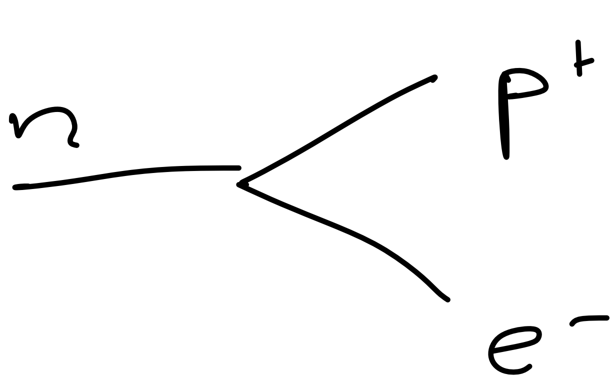
$$E_e^2 = \frac{(m_n^2 - m_p^2 + m_e)^2}{2 m_n} \longrightarrow m_e^2$$

$m_n \to m_p + m_e$



Pauli (1930) : + neutrino

Beta decay

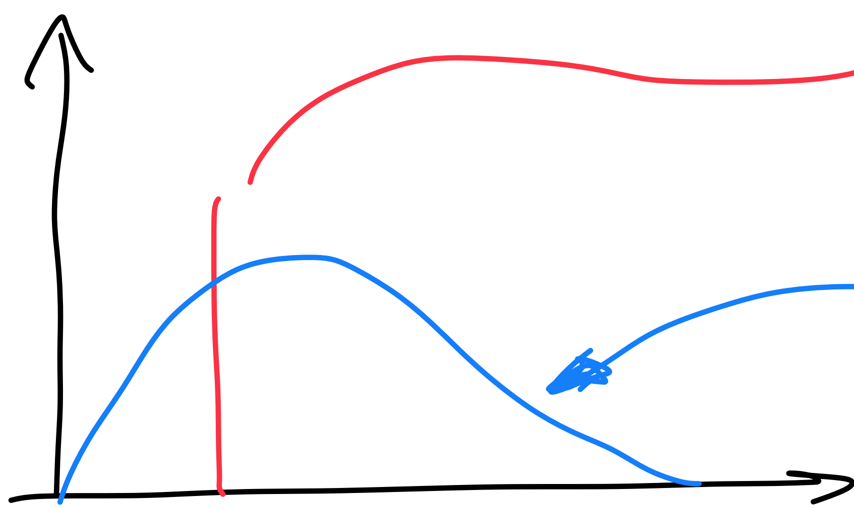


$1 \rightarrow 2$

Ex: $p_n = p_p + p_e$

$$E_e^2 = \frac{(m_n^2 - m_p^2 + m_e)^2}{2 m_n} \rightarrow m_e^2$$

$m_n \rightarrow m_p + m_e$



E and Spin conservation

Pauli (1930) : + neutrino

Fermi theory (1933)

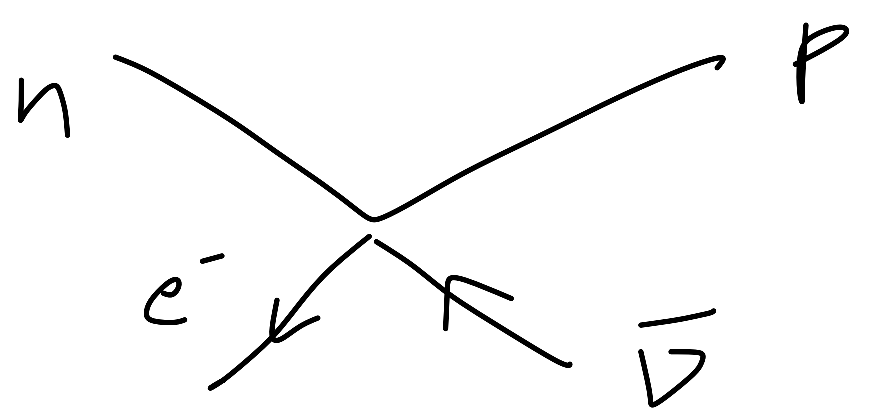
Current x current

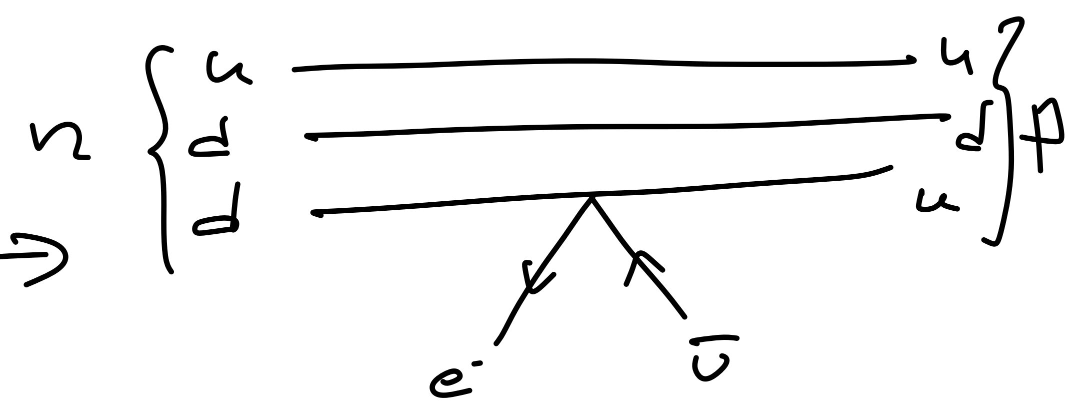
$$\mathcal{L}_F \propto G_F \, J_{had,\mu} \times J_{lep}^{\mu}$$

n destroyed and p, e, ν created

$$\bar{p}\,\Gamma_\mu\, n \qquad \bar{e}\,\Gamma^\mu\, \nu$$

$$\Gamma_\mu \sim \gamma^\mu \qquad \Gamma^\mu \sim \gamma^\mu$$





$$\mathcal{L}_F \propto G_F(\bar{u}\,\gamma^\mu d)\,(\bar{e}\,\gamma_\mu \nu)$$

Refused by Nature

C. Degrande

Fermi and dimension

$c = 1 = \hbar$

$$S = \int d^4x \, \mathcal{L}$$

$[\;] = \frac{1}{mass^4}$, $[\;] = mass^4$

Dimensionless

$$\mathcal{L}_{DIRAC} \ni \bar{\Psi} \not{\partial} \psi \,, \; m \bar{\Psi} \psi$$

$[\;] = mass^{3/2}$

EFT

$$\Rightarrow [\bar{\Psi}_1 \gamma_\mu \psi_2 \bar{\Psi}_3 \gamma_\mu \psi_4] = mass^6 \Rightarrow [G_F] = mass^{-2}$$

dimension > 4

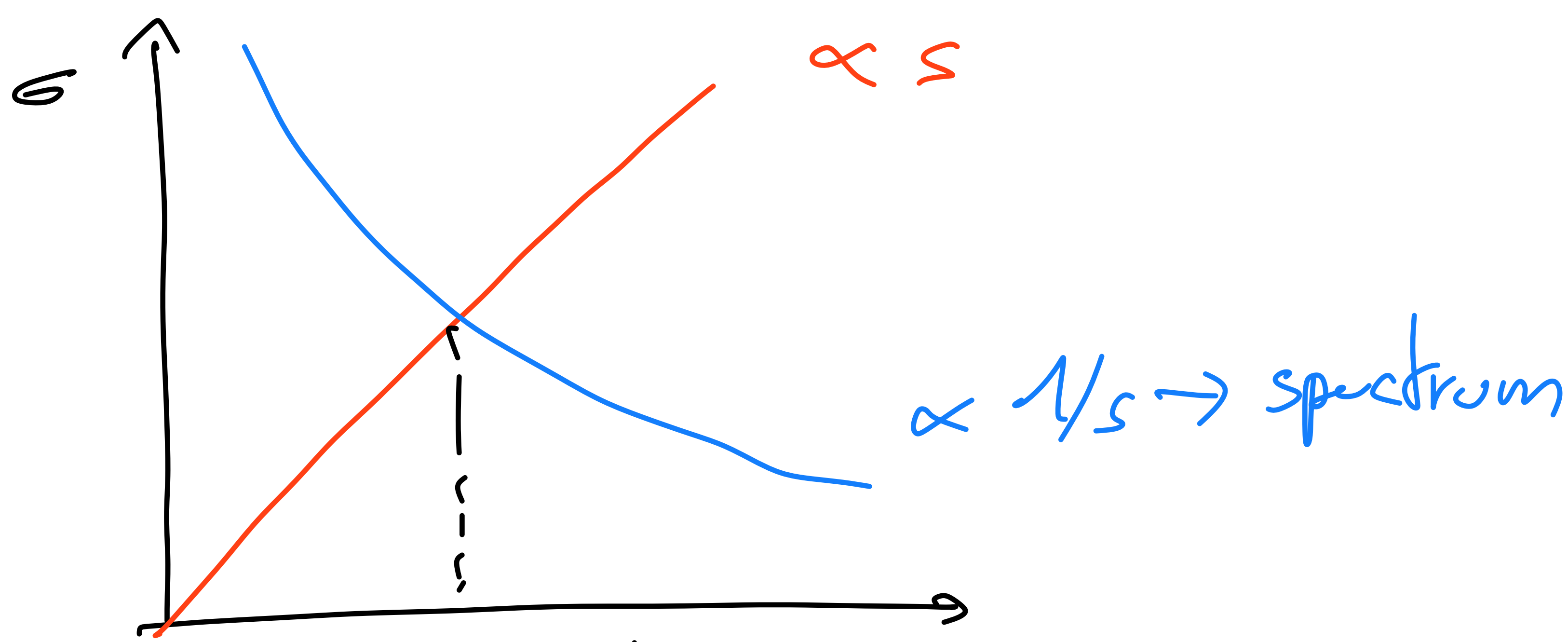
Unitarity violation

$\sigma_{FERMI} \propto G_F^2 \times s \rightarrow$ Proba > 1

$s \rightarrow$ div

$\sigma_{FERMI} \rightarrow [\;] = \dfrac{1}{\text{mass}^2}$

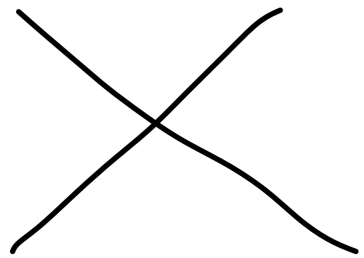
When?



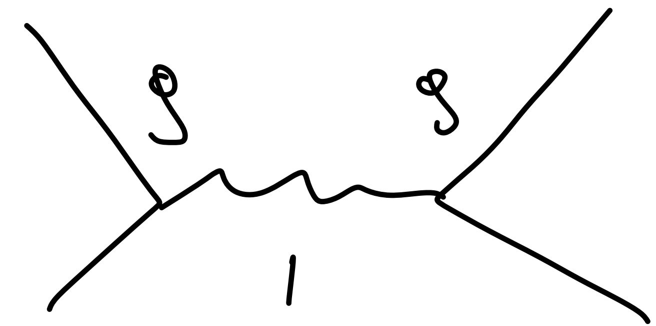
$s = G_F^{-1} \sim (300\ \text{GeV})^2$

C. Degrande

Unitarity violation

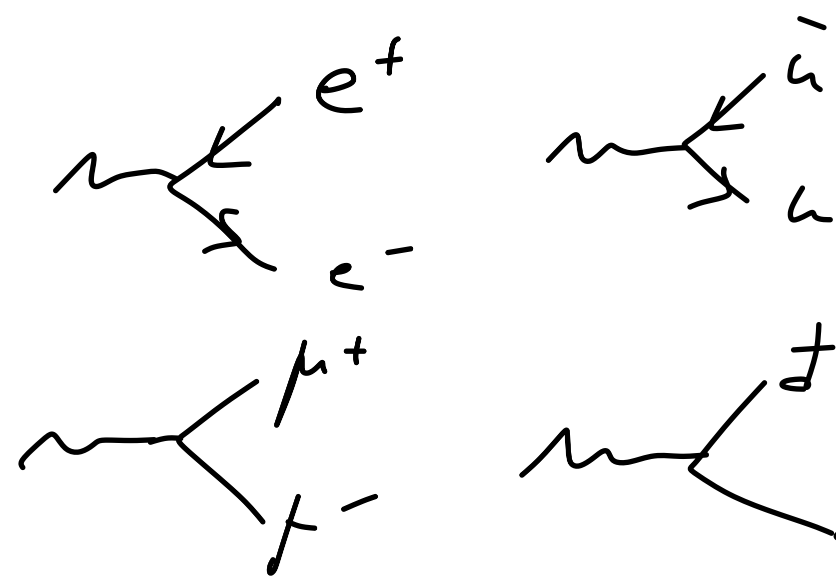


4F but in QED



$$-\frac{g^2}{m^2} \sim G_F \qquad \xleftarrow{p^2 \ll m^2} \qquad \frac{1}{p^2-m^2}$$

But in QED
- Always the same fermion
- Massless gauge boson



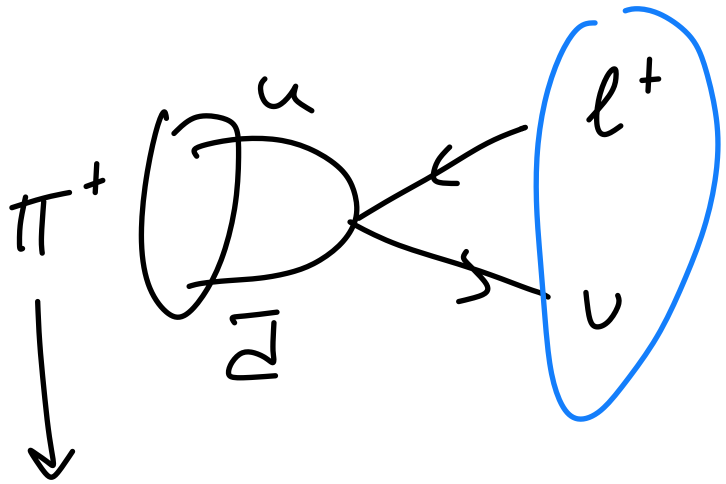
[no ν
$G_\nu = 0$]

$\bar{\Psi} \not{D} \psi$

$D \to \partial_\mu - i g A_\mu$

C. Degrande

Pion decay



$$J_{lep\,\mu} \ni \bar{\nu}\gamma^\mu \ell$$

$$J^\mu_{had} \ni \pi^\pm$$

$$\mathcal{L}_{KG} \ni m^2 \phi^\dagger \phi$$

$$[\phi] = \text{mass}$$

$$V \Longrightarrow J^{had}_\mu \sim f_\pi\, \partial_\mu \pi$$

$$[f_\pi] = \text{mass}\,.$$

$$\mathcal{L}_{FERMI} \ni G_F\, f_\pi\, \partial_\mu \pi^+\, \bar{\nu}\gamma^\mu \ell = G_F\, f_\pi\, \pi^+ \Big(\bar{\nu}\underbrace{\not{\partial}\ell}_{m_\ell \ell} + \underbrace{(\partial_\mu \bar{\nu})\gamma^\mu \ell}_{0\cdot\bar{\nu}}\Big)$$

by part

Dirac

$$M \propto G_F\, f_\pi\, m_\ell$$

Pion decay

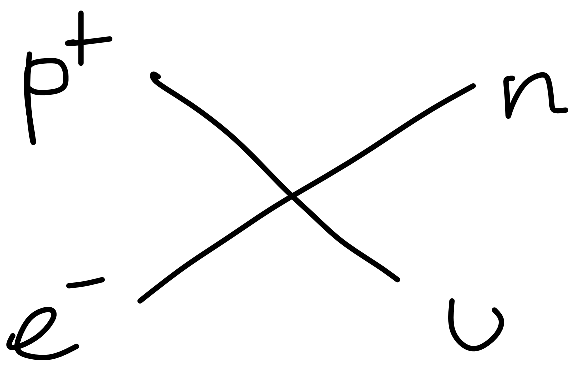
$$\Gamma \propto G_F^2 f_\pi^2 m_\ell^2 m_\pi \underbrace{\left(1-\frac{m_\ell^2}{m_\pi^2}\right)^2}_{\to 0 \text{ if } m_\ell \to m_\pi}$$

$[\Gamma] = \text{mass}$

$$\frac{Br(\pi \to e\nu)}{Br(\pi \to \mu\nu)} \simeq \frac{m_e^2}{m_\mu^2\left(1-\frac{m_\mu^2}{m_\pi^2}\right)^2} \simeq 1.23\, 10^{-4}$$

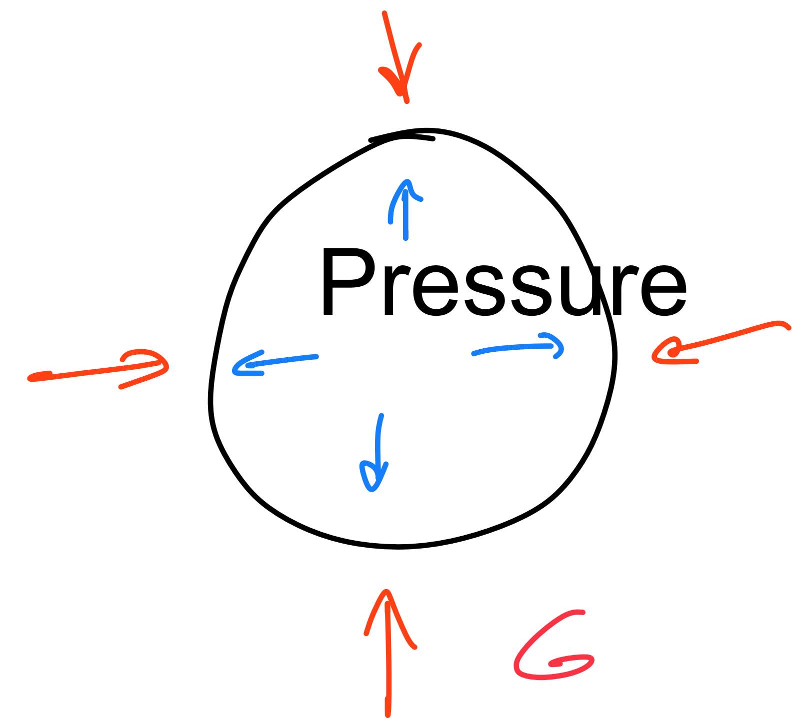
Because V interaction

Inverse beta decay



$\longrightarrow$ star collapse

neutron star (fermi pressure)



produce neutrinos

Ex: momentum in CM

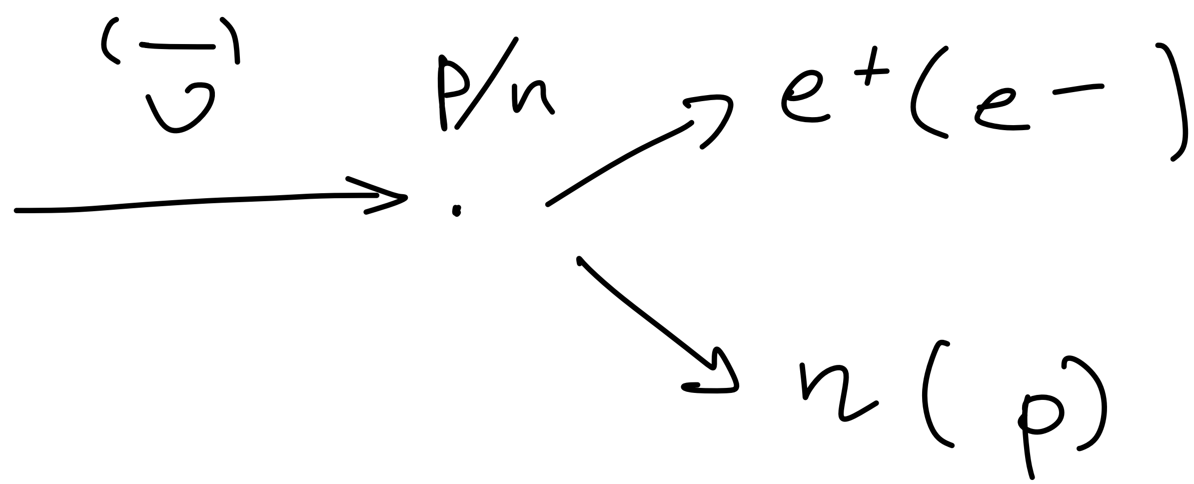
$$\Delta m = m_n - m_p$$

$$|\vec{p}_i| = \frac{m_n^2 - m_p^2}{2 m_n} \simeq \Delta m \simeq 1.3\ \mathrm{MeV}$$

$$1\ \mathrm{eV} \simeq 10^4\ \mathrm{K} \implies 1.3\ \mathrm{MeV} \sim 10^{10}\ \mathrm{K}$$

C. Degrande

Neutrino detection



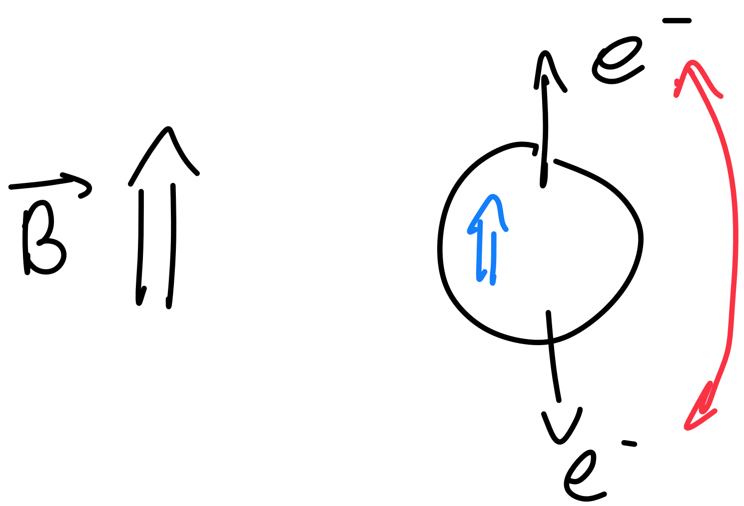
EX: scan cross-section fermi for energies from 1 GeV to 100 GeV
Same in the SM

Parity violation

$\Gamma^\mu = \gamma^\mu$?

1956 Lee-Yang

Exp 1957 Wu



or

$$^{60}_{27}Co \longrightarrow {}^{60}_{28}Ni + e^- + \bar{\nu}_e$$

$$^{60}_{28}Ni \longrightarrow 2\gamma$$

$$\langle \vec{p}_e \cdot \vec{B} \rangle \neq 0 \implies \cancel{P}$$

Averaged value over the events

Parity

$\vec{x} \longrightarrow -\vec{x}$ $\qquad\qquad$ $t \longrightarrow t$

$\dot{\vec{x}} = \dfrac{\partial \vec{x}}{\partial t} \longrightarrow -\dot{\vec{x}}$ $\qquad \Longrightarrow \qquad$ $\vec{p} \longrightarrow -\vec{p}$

$\vec{E} \longrightarrow -\vec{E}$ $\qquad$ Vector

$\vec{B} \longrightarrow +\vec{B}$ $\qquad$ Axial vector or pseudo vector

$\mathcal{L}_{QED} \propto A_\mu \bar{\psi} \gamma^\mu \psi$ $\qquad$ P-conserving

$\hookrightarrow (\phi, \vec{A})$

$A^\mu \longrightarrow A_\mu$

$\underset{\displaystyle J^\mu}{\underset{\parallel}{\bar{\psi} \gamma^\mu \psi}} \longrightarrow \bar{\psi} \gamma_\mu \psi$

C. Degrande

Parity

Axial vector spin $\sim \vec{L} = \vec{r} \times \vec{p}$

Spin projector $s_\mu \gamma^\mu \gamma^5$

$s^2 = -1$

$s \cdot p = 0$

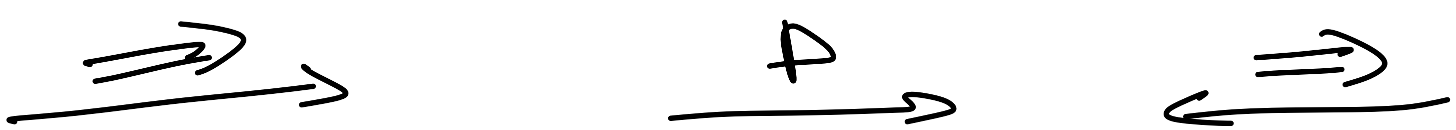
$\Downarrow$

$s = \frac{1}{m}\left(|\vec{p}|, \frac{E}{|\vec{p}|}\vec{p}\right)$

Helicity projector

$P_\pm = \frac{1 \pm \not{s}\gamma^5}{2}$

$m \to 0$ $\gamma_{R/L} \; \frac{1 \pm \gamma_5}{2} \longrightarrow$ Chirality projector



$\psi_L = \gamma_L \psi \longrightarrow \psi_R$

$\psi_R = \gamma_R \psi \longrightarrow \psi_L$

Parity

$$J^\mu = \bar\psi \gamma^\mu \psi = \bar\psi \gamma^\mu (\gamma_L + \gamma_R)\psi$$
$$= \bar\psi_L \gamma^\mu \psi_L + \bar\psi_R \gamma^\mu \psi_R \xrightarrow{P} J_\mu$$

$$A^\mu = \bar\psi \gamma^\mu \gamma^5 \psi = \bar\psi \gamma^\mu (\gamma_R - \gamma_L)\psi$$
$$= \bar\psi_R \gamma^\mu \psi_R - \bar\psi_L \gamma^\mu \psi_L \xrightarrow{P} -A_\mu$$

Maximal violating interaction (1958)

Feynman Gell-Mann Marshak Sudarshan

Weak interaction with the left only

$V_\mu \to M_V \qquad M_V \xrightarrow{P} M_V$

$A_\mu \to M_A \qquad M_A \xrightarrow{P} -M_A \qquad |M_A|^2 \xrightarrow{P} |M_A|^2$

Max if $M_A = \pm M_V$

$$|M_V + M_A|^2 = |M_V|^2 + |M_A|^2 + 2\,\mathrm{Re}(M_V M_A^*)$$
$$\xrightarrow{P} |M_V|^2 + |M_A|^2 - 2\,\mathrm{Re}(M_V M_A^*)$$

C. Degrande

Fermi summary

$$\mathcal{L}_F \propto G_F \, \bar{u}_L \gamma^\mu d_L \; \bar{\nu}_L \gamma_\mu \ell_L$$

Requests: pure left

massive Vector boson

changing particle flavour

$\hookrightarrow$ $e \leftrightarrow \nu$, $u \leftrightarrow d$

All the generations but only the leptons for now

Ex : $\sigma(e^- \mu^+ \to \nu_e \bar{\nu}_\mu)$ in Fermi and SM

at $s = 1, 5, 50, 500$

Weak group

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F (\bar{\nu}_{\mu L} \gamma^\alpha \mu_L)(\bar{e}_L \gamma_\alpha \nu_{eL}) + \text{other flavours}$$

solution : $L_e = \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}$, $L_\mu = \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F \bar{L}_\mu \gamma^\alpha T^- L_\mu \bar{L}_e \gamma_\alpha T^+ L_e$$

$$T^- = \begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix} \qquad T^+ = (T^-)^\dagger = \begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}$$

$$J_L^\mu = \sum_\ell \bar{L}_\ell \gamma^\alpha T^- L_\ell$$

$$\mathcal{L}_{FERMI} = -2\sqrt{2}\, G_F J_L^\mu J^\dagger_{\mu L}$$

Weak group

In QED $\quad \psi \to e^{iq\theta(x)}\psi$

$$\partial_\mu \longrightarrow D_\mu = \partial_\mu - i\underset{\downarrow}{q} A_\mu$$

charge replaced by $T^{\pm}$

Do not commute: non abelian

symmetry group close under anticommutation

$$[T^+, T^-] = -2T^3 = \begin{pmatrix} -1 & 0 \\ 0 & 1 \end{pmatrix} = -2\begin{pmatrix} 1/2 & 0 \\ 0 & -1/2 \end{pmatrix}$$

$$T^1 = \frac{T^+ + T^-}{2} = 1/2\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$T^2 = i\frac{(T^+ - T^-)}{2} = 1/2\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

$$[T^i, T^j] = i\varepsilon^{ijk} T^k$$

$SU(2): U = e^{i\vec{\alpha}\cdot\vec{T}}$

$\det U = 1$

$\Updownarrow$

$\mathrm{Tr}(T^i) = 0$

Neutral currents and right leptons

changed currents and group $\Longrightarrow$ neutral currents

$$J_3^\alpha = J_{NC}^\alpha = \bar{L}_\ell \gamma^\alpha T^3 L_\ell = \underbrace{\bar{\nu}_{\ell L} \gamma^\alpha \nu_{\ell L}}_{\text{Not EM}} - \bar{\ell}_L \gamma^\alpha \ell_L$$

$Q(\nu) = 0$

No charged currents with the right fermions

$\nu_R \, , \; \ell_R \sim 1_{SU(2)}$ $\quad Tr(1 \times 1) = 0$

$= 0$

$$m \bar{\psi} \psi = m (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

Not invariant under SU(2)

C. Degrande

Electroweak group

$+\ U(1)_Y \neq EM \longrightarrow [Q, T^a]$

All particles in an SU(2) multiplet have the same charge

$$\psi \longrightarrow e^{ig_2 \vec{\alpha}(x)\cdot\vec{T} + i g_1 Y \theta(x)}\ \psi$$

$$D_\alpha = \partial_\alpha - i g_2 \vec{W}_\alpha \cdot \vec{T} - i g_1 Y B_\alpha$$

$$B_\mu \longrightarrow B_\mu + \partial_\mu \theta(x)$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Invariant

$$\vec{W}_\mu \longrightarrow \vec{W}_\mu + \partial_\mu \vec{\alpha}(x) + g_2 (\underbrace{\vec{W}_\mu \times \vec{\alpha}}_{\varepsilon^{ijk} W_\mu^j \alpha^k})$$

$\bar{\psi} \cancel{D} \psi$

$$\downarrow$$

$$[\ ,\ ]$$

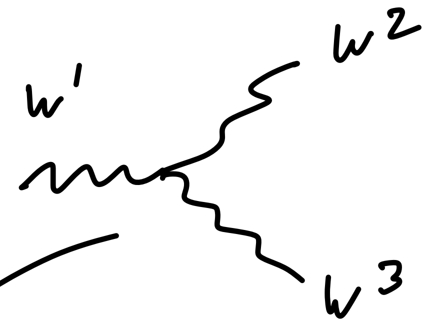
$\boxed{\text{Non Abelian}}$

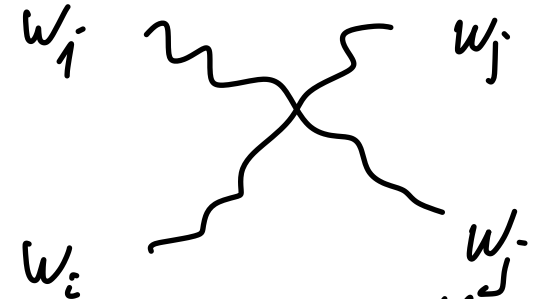
$$T^i W_{\mu\nu}^i = \partial_\mu W_\nu^i T^i - \partial_\nu W_\mu^i T^i - i g_2 [W_\mu^j T^j, W_\nu^k T^k]$$

C. Degrande

Pheno of non abelian gauge theory

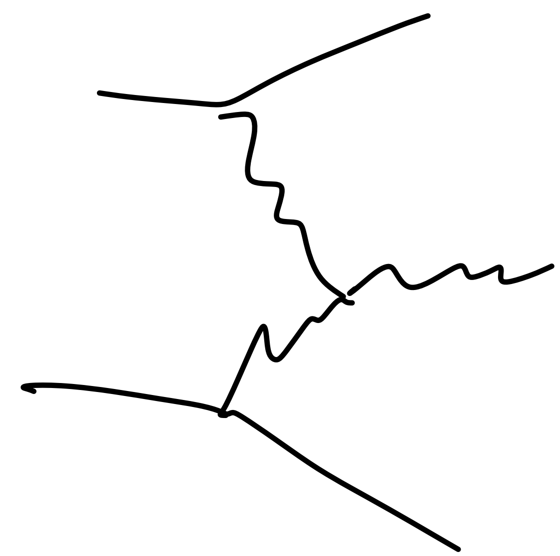
$W^i_{\mu\nu} W^{\mu\nu}_i \ni$





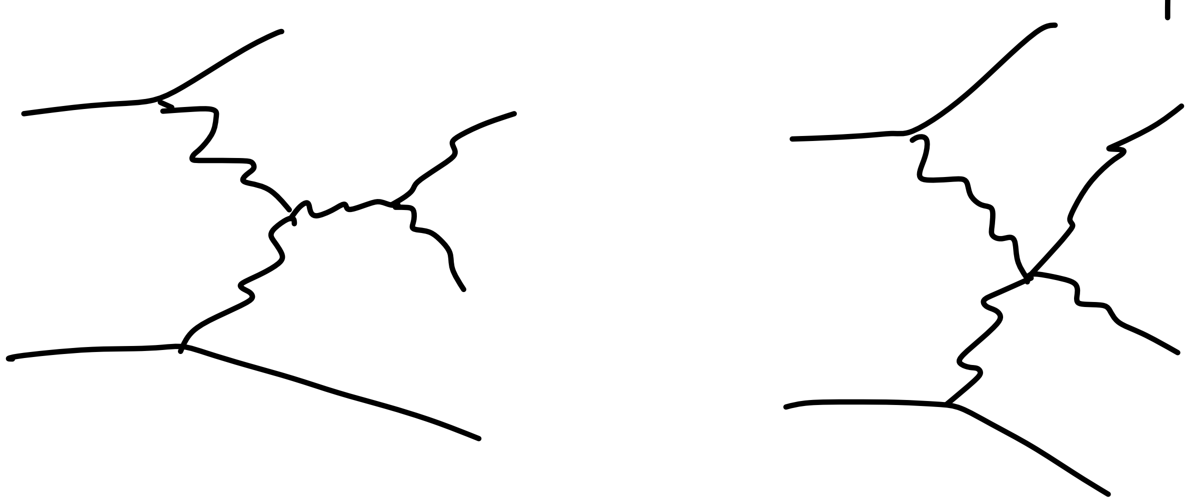
$\propto p^\mu \eta^{\alpha\beta}, g_2$ $\propto \eta^{\mu\nu}\eta^{\alpha\beta}, g_2^2$

$W^+ W^- \gamma$ since $Q(W^+) = 1$



VBF

DIBOSON



VBS

Z-A mixing

$$\mathcal{L} \ni \bar{L} \not{D} L + \bar{\nu}_R \not{D} \nu_R + \bar{l}_R \not{D} l_R$$

$$= \bar{L} \not{\partial} L + \bar{\nu}_R \not{\partial} \nu_R + \bar{l}_R \not{\partial} l_R - i\sqrt{2}\, g_2 \bar{L} \not{W}^+ T^- L$$

$$- i\sqrt{2}\, g_2 \bar{L} \not{W}^- T^+ L$$

$$\mathcal{L}_{NC} \; " \; - i g_2 \bar{L} \not{W}_3 T^3 L - i g_1 \bar{L} Y_L \not{B} L - i g_1 Y_{\nu_R} \bar{\nu}_R \not{B} \nu_R - i g_1 Y_{l_R} \bar{l}_R \not{B} l_R$$

$$W^+ = \frac{W_1 - i W_2}{\sqrt{2}} \qquad W^- = \frac{W_1 + i W_2}{\sqrt{2}}$$

$$\begin{pmatrix} W_3 \\ B \end{pmatrix} = \begin{pmatrix} c_W & s_W \\ -s_W & c_W \end{pmatrix} \begin{pmatrix} Z \\ A \end{pmatrix} \xrightarrow[\text{s.t.}]{c_W,\, s_W} \mathcal{L}_{NC} \ni i e Q_F A_\mu \underline{\bar{F} \gamma^\mu F}$$

VECTOR

$$\left.\begin{array}{l} Q(\nu) = 0 \\ Q(e) = -1 \end{array}\right\} \Longrightarrow \begin{array}{l} e = g_2 s_W = g_1 c_W \\ Y_L = -1/2 \end{array}$$

$$Q = T^3 + Y$$

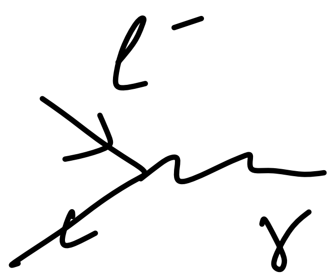
C. Degrande

FFV

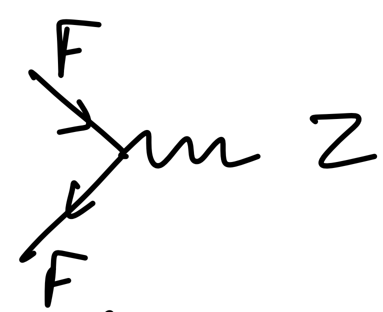
$$\Longrightarrow \quad Y_{\nu_R} = 0 \longrightarrow$$ Not interacting, not in the SM

$$Y_{e_R} = -1$$

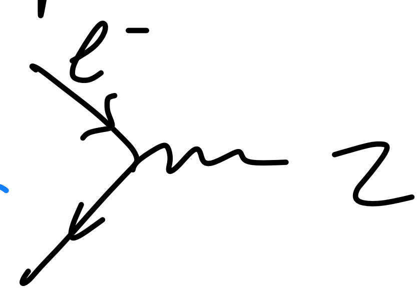
$$\mathcal{L}_{NC} = \sum_{F=\nu_R,\, \ell_R,\, L} \left\{ -i e Q_F A_\mu \bar{F} \gamma^\mu F - i \frac{e}{s_w c_w} Z_\mu \left(T^3 - s_w^2 Q\right) \right\}$$



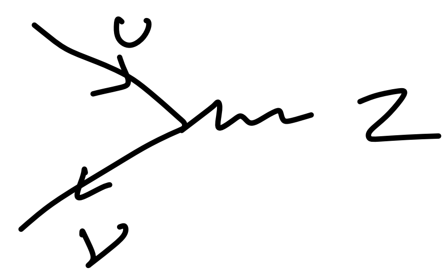
$$i q_\ell \gamma^\mu$$



$$\frac{ie}{s_w c_w}\left(T^3 - s_w^2 Q\right)\gamma^\mu$$

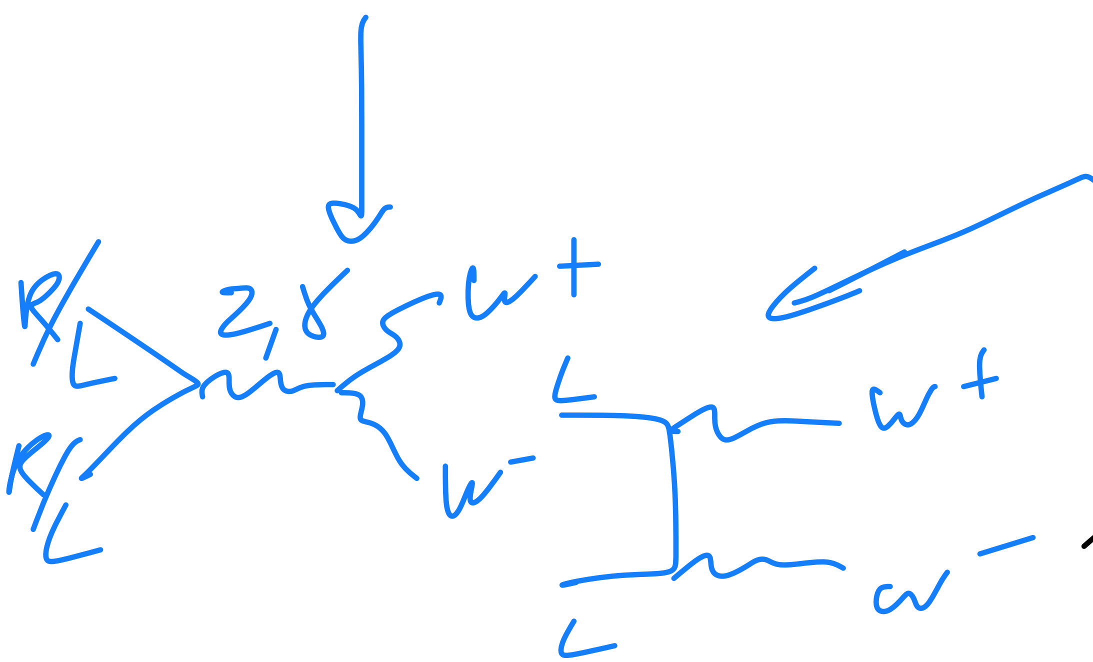


$$\frac{ie}{s_w c_w}\left[\left(-\tfrac{1}{2} - s_w^2\right)\gamma^\mu \gamma_L + \left(-s_w^2\right)\gamma^\mu \gamma_R\right]$$



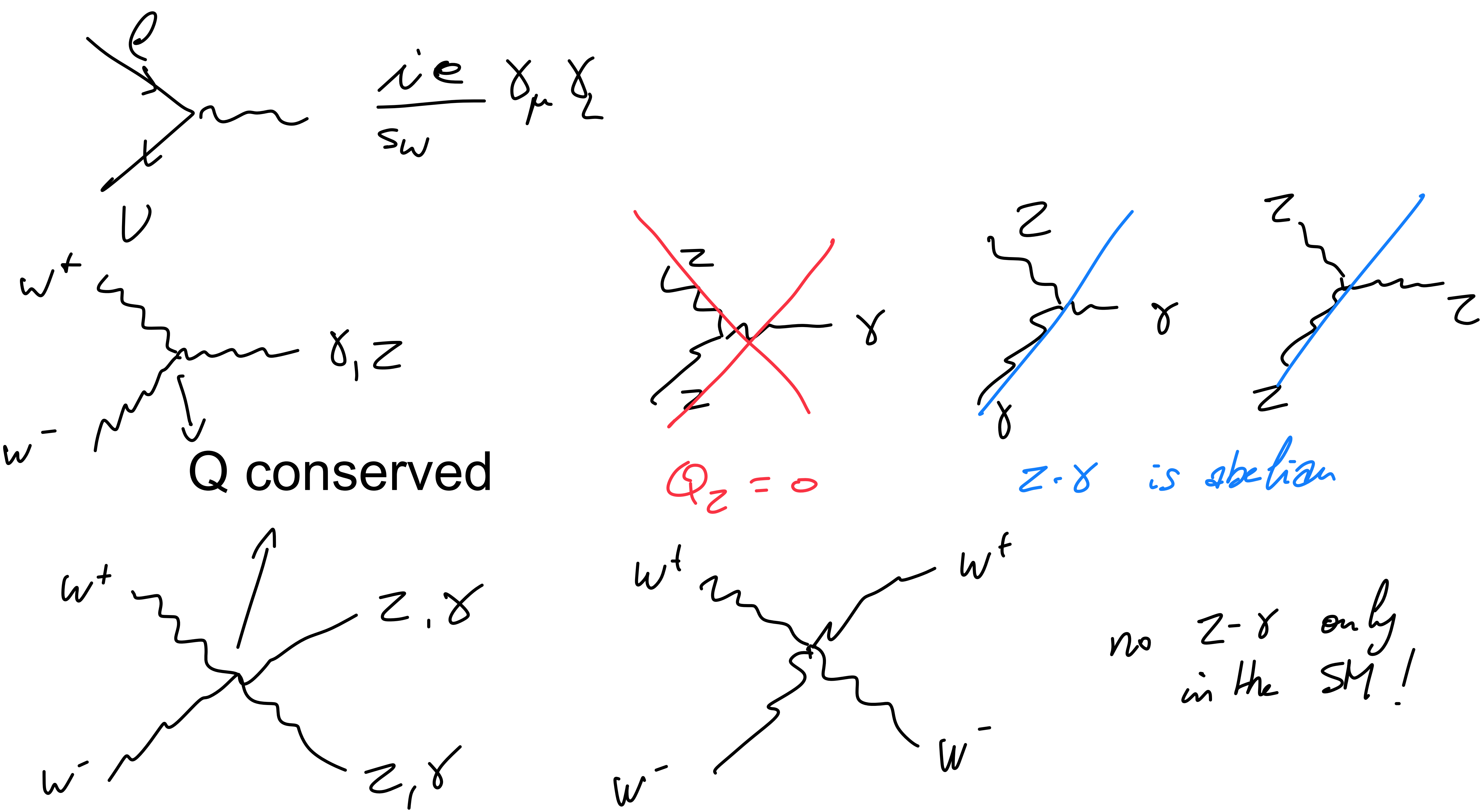
$$\frac{ie}{s_w c_w} \quad \tfrac{1}{2}\gamma^\mu \gamma_L$$

no γ_R!



C. Degrande

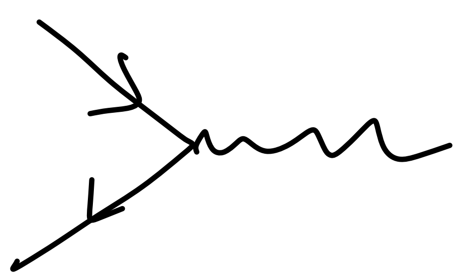
More electroweak interactions



C. Degrande

Z production

e^- q



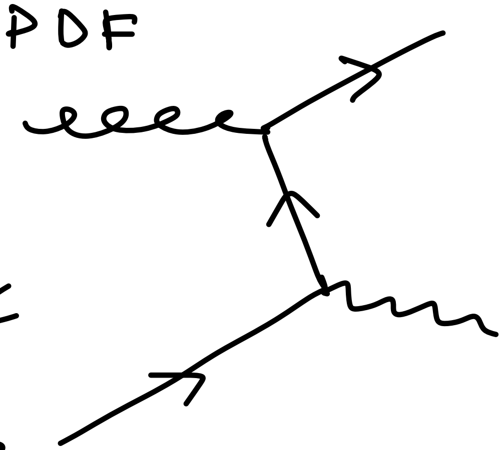
e^+ $\bar{q}$

LEP

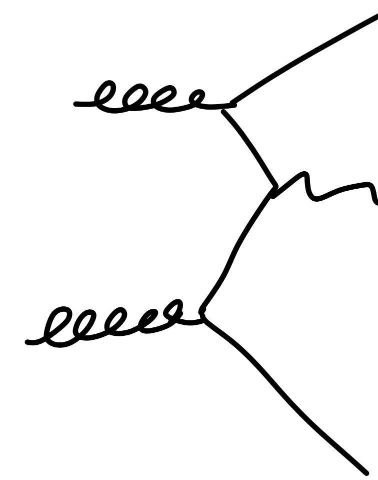
LHC

TEVATRON

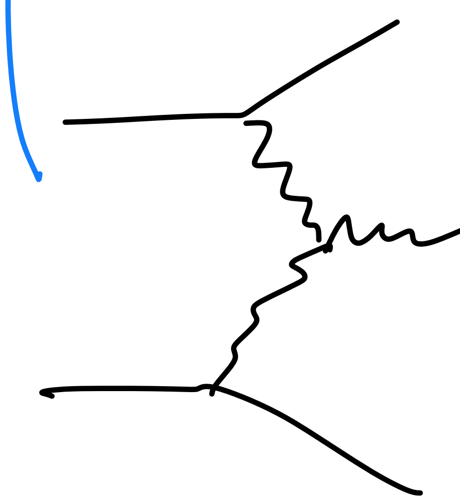
PDF



Z+j



large bkg



- $\dfrac{\sigma(Zj)}{\sigma(Z)}(p_T^j)$ ⚠ IR

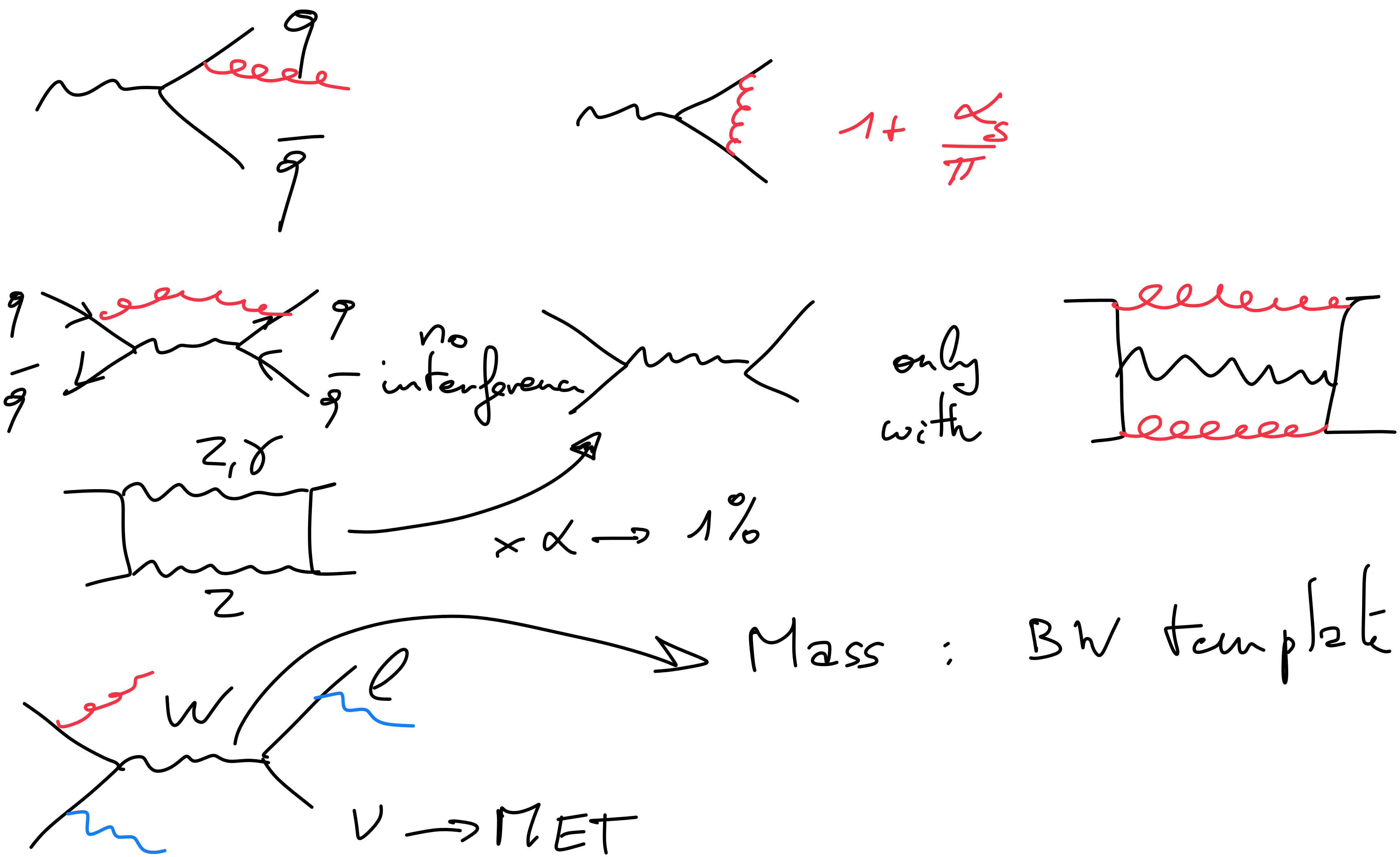
rapidity gap, large m_{jj}, ...

- $\dfrac{\sigma^{EW}(Zjj)}{\sigma^{QCD}(Zjj)}$ → find cut to improve

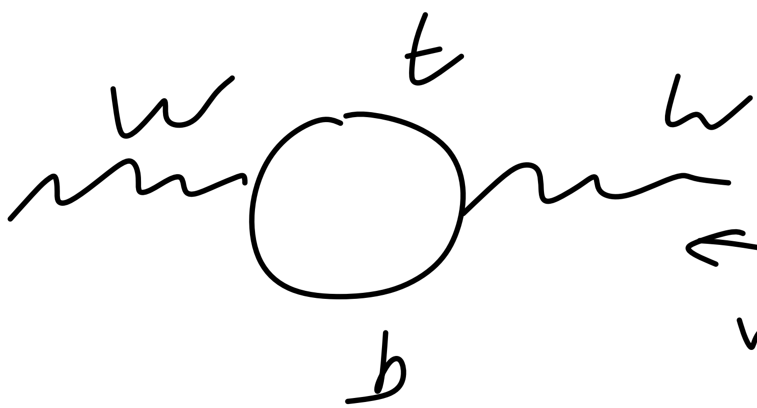
NLO : ? Mixed EW / QCD

- $\sigma(pp \to Z \to \ell\ell) / \sigma(pp \to \ell\ell)$ + ≠ in distributions

More Z production + decay

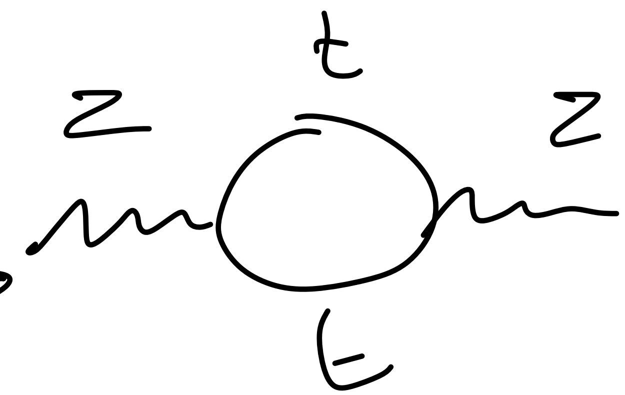


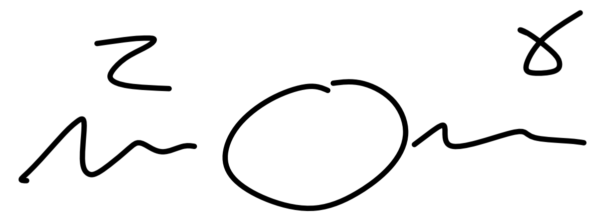
Electroweak precision tests



mass relation

ρ

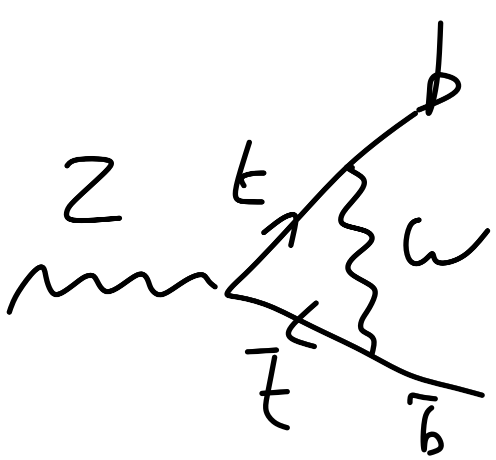




change mixing

m_t from LEP !

corr $\propto m_t^2$



$\longrightarrow$ 1‰ + $N_\nu \simeq 3$

Exercises

$\sigma(pp \to Z)$ $\underbrace{\text{+ scale variation}}_{\text{TH ERROR}}$

@ LO, NLO

- Discuss shape uncertainties at LO?
- Fixed order vs Parton shower
- Number of jets

WW scattering

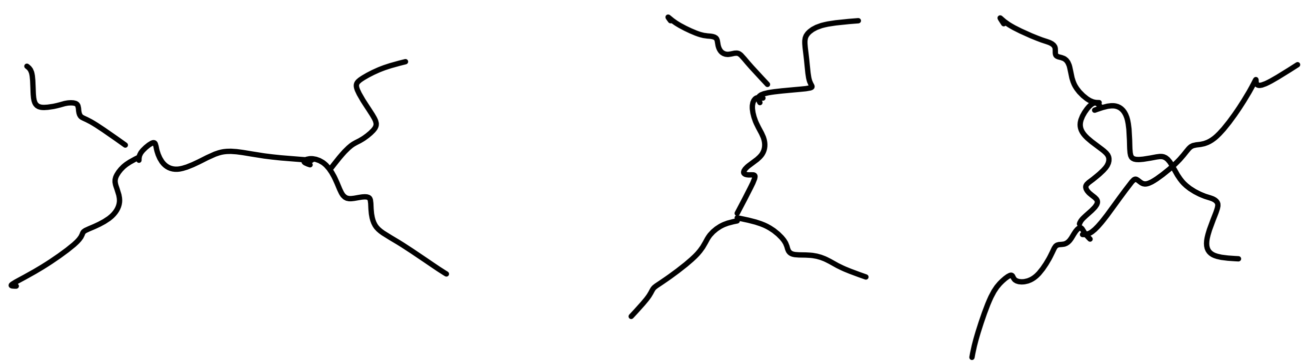
$W_L W_L \to W_L W_L$

$p^\mu = (E, 0, 0, p)$ $\quad \epsilon_\pm = \frac{(0, 1, \pm i, 0)}{\sqrt{2}}$

$\epsilon_L = \frac{1}{m}(p, 0, 0, E)$

↳ longitudinal, only if massive
otherwise transverse only

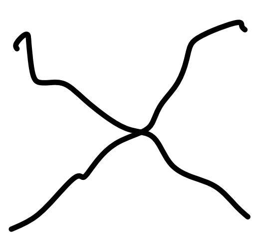
3 pt only



$$|M_1 + M_2|^2 \propto \frac{(s^2 + 4ts + t^2)}{m_W^4}$$

$$\Rightarrow \sigma \sim s \qquad \left(\sigma \sim \frac{|M|^2}{s}\right)$$

3 pt and 4 pt



$$|M_1 + M_2 + M_3|^2 \propto \frac{(-s-t)}{m_W^2}$$

$\sigma \sim$ const

Gauge invariance implies massless boson

C. Degrande

Electroweak symmetry breaking

The U(1) case

$$A_\mu \longrightarrow A_\mu + \partial_\mu \alpha(x)$$

$$D_\mu \longrightarrow \partial_\mu - ie A_\mu$$

$$\phi \longrightarrow e^{ie\alpha(x)} \phi$$ complex field or not charged

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + D_\mu \phi^\dagger D^\mu \phi - V(\phi)$$

scalar potential

Renormalisable $\Rightarrow d \leq 4$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$

$$\mu^2 > 0 \longrightarrow \langle \phi \rangle = 0$$

$$\mu^2 < 0 \longrightarrow \langle \phi \rangle = \sqrt{\frac{-\mu^2}{2\lambda}} \equiv \frac{v}{2}$$ chosen real by gauge inv.

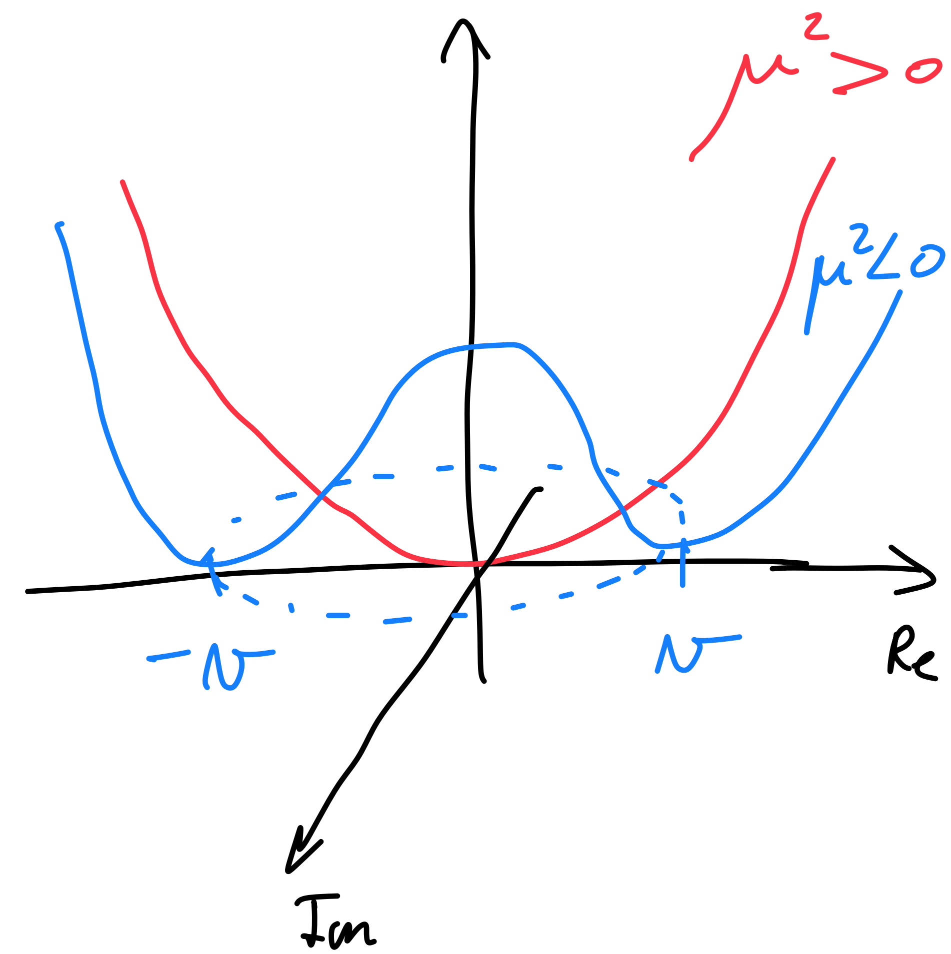
C. Degrande

Minimum of the potential

$\langle \phi \rangle$ min of V

$$\frac{\partial V}{\partial v} = \frac{\partial}{\partial v}\left(\mu^2 \frac{v^2}{2} + \frac{\lambda v^4}{4}\right) = (\mu^2 + \lambda v^2)\, v$$

$v = 0$ $\qquad$ $v^2 = -\frac{\mu^2}{\lambda}$



Spontaneous Sym Breaking

$$\phi \equiv \frac{1}{\sqrt{2}} e^{i\chi/v} (v + h)$$

$\hookrightarrow [\,] = $ mass like h, χ

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e v A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu$$
$$+ \frac{1}{2}\left(\partial_\mu h \partial^\mu h + 2\mu^2 h^2\right) + \frac{1}{2} \partial_\mu \chi \partial^\mu \chi$$

Massive gauge boson

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - e v A_\mu \partial^\mu \chi + \frac{e^2 v^2}{2} A_\mu A^\mu$$
$$+ \frac{1}{2} (\partial_\mu h \partial^\mu h + 2\mu^2 h^2) + \frac{1}{2} \partial_\mu \chi \partial^\mu \chi$$

1 gauge boson of mass

1 real scalar field h of mass^2 $= -2\mu^2 > 0$

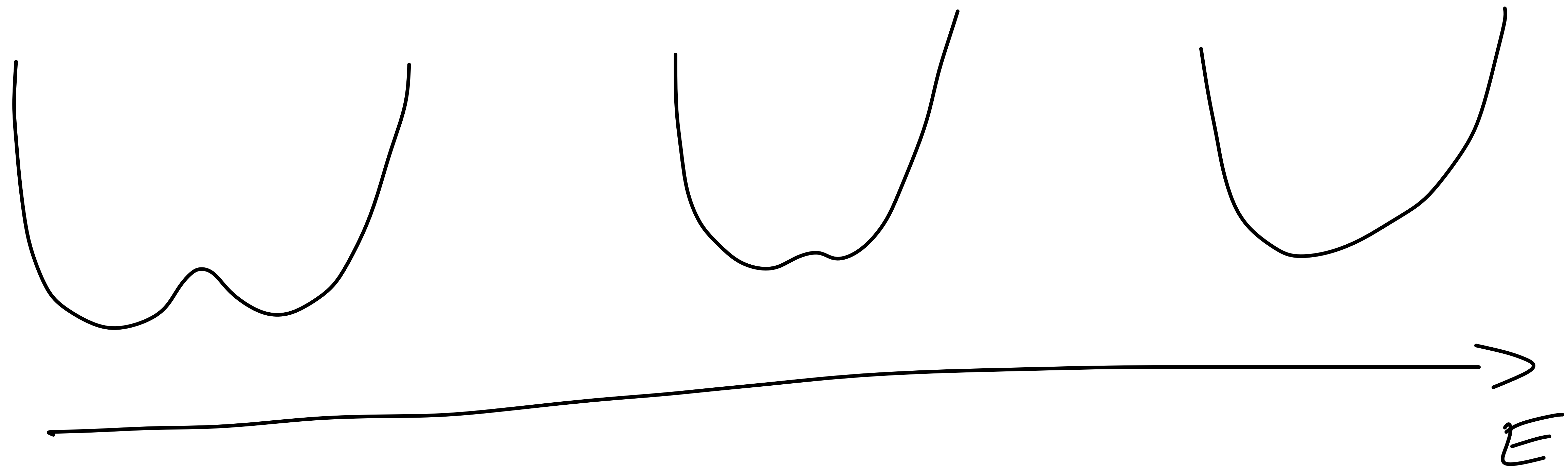
1 massless scalar field χ mixed with A

→ Unphysical: removed by gauge transformation
Only derivative interactions: Goldstone boson(massless)
transforms linearly with the gauge $\chi \rightarrow \chi + \alpha e v$

Massive vector = 3 d.o.f.=1 scalar + 1 massless vector

C. Degrande

At high energy



symmetry is restored

Electroweak symmetry breaking

$$SU(2)_L \times U(1)_Y \longrightarrow U(1)_{EM}$$

$\downarrow$

Broken $\Longrightarrow$ $\phi \sim 2, 3, 4, \dots$ of $SU(2)_L$ not 1

$Q = T^3 + Y$ $\longrightarrow$ 1 neutral component a break EM

$$Y = \pm 1/2$$

$$\phi = \begin{pmatrix} \phi^+ \\ \frac{h + \sigma + v}{\sqrt{2}} \end{pmatrix} \Rightarrow \langle \phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$\hookrightarrow 0$ chosen by gauge

Same potential

$$V(\phi) = -\mu^2 \phi^+ \phi + \lambda (\phi^+ \phi)^2 \qquad v^2 = \frac{\mu^2}{\lambda}$$

C. Degrande

Vector bosons masses

$$\mathcal{L}_S = D_\mu \phi^\dagger D^\mu \phi - V(\phi)$$

$$D^\mu \to \partial^\mu - i g_2 T^a W^{a\mu} - i g_1 B_\mu Y$$

$$\ni \frac{1}{8} \begin{pmatrix} 0 & v \end{pmatrix} \left(g_2 \begin{pmatrix} W_3^\mu & \sqrt{2} W^{+\mu} \\ \sqrt{2} W^{-\mu} & -W_3^\mu \end{pmatrix} + g_1 \begin{pmatrix} B_\mu & 0 \\ 0 & B_\mu \end{pmatrix} \right)^2 \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$= \frac{v^2}{8} \left(2 g_2^2 W_\mu^+ W^{\mu -} + (g_1 B_\mu - g_2 W_3^\mu)^2 \right)$$

$$= m_W^2 W_\mu^+ W^{\mu -} + \frac{m_Z^2}{2} Z_\mu Z^\mu$$

$$\Rightarrow m_W^2 = \frac{g^2 v^2}{4} = \left(\frac{e v}{2 s_W} \right)^2 \qquad s_W = g_1 / \sqrt{g_1^2 + g_2^2}$$

$$Z_\mu = \frac{(-g_1 B_\mu + g_2 W_{3\mu})}{\sqrt{g_1^2 + g_2^2}} = -s_W B_\mu + c_W W_\mu^3 \qquad c_W = g_2 / \sqrt{g_1^2 + g_2^2}$$

$\to$ Normalization

C. Degrande

Vector bosons masses

$$M_Z^2 = \frac{1}{4}\left(g_1^2 + g_2^2\right) v^2 = \left(\frac{ev}{2 s_W c_W}\right)^2$$

$$\rho = \frac{m_W^2}{m_Z^2\, c_W^2} = 1 \quad \text{in the SM}$$

if $\xi \sim 3_{SU(2)}$ with $\langle \xi \rangle \longrightarrow \rho = 1 - \frac{2\langle \xi^0\rangle^2}{\langle \phi^0\rangle^2}$

Protected by custodial symmetry, only broken by gauge and Yukawa interactions

Fermi $\quad \frac{g_2^2}{m_W^2} \propto \frac{1}{v^2} \Rightarrow G_F = \frac{1}{\sqrt{2}\, v^2}$

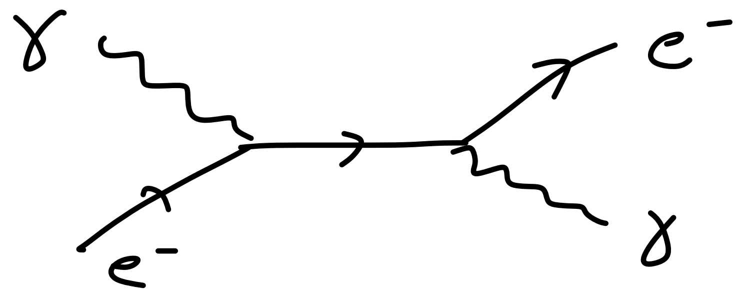
$v \cong 246$ GeV

$s_W^2 \cong 0.23$

$\alpha_{EM}(m_e) \cong \frac{1}{137}$

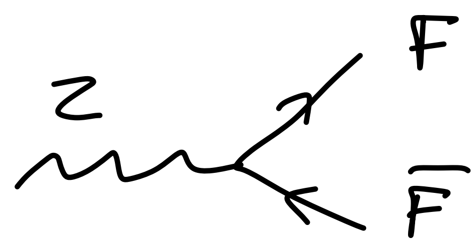
Masses predictions

$\alpha_{EM}(m_e)$

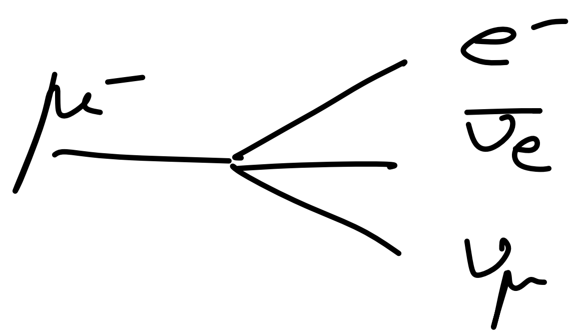


Very soft Compton scattering

s_W^2



G_F



(G_μ)

$m_W \cong 80\ \text{GeV}$

$m_Z \cong 91\ \text{GeV}$

More about EWSB

3 Goldstone bosons $\sigma\ ,\ \phi^+\ ,\ \phi^-$

$\Updownarrow$

3 broken generators

$SU(2)_L \otimes U(1)_Y \longrightarrow U(1)_{EM}$

$3 \quad + \quad 1 \quad \longrightarrow \quad 1$

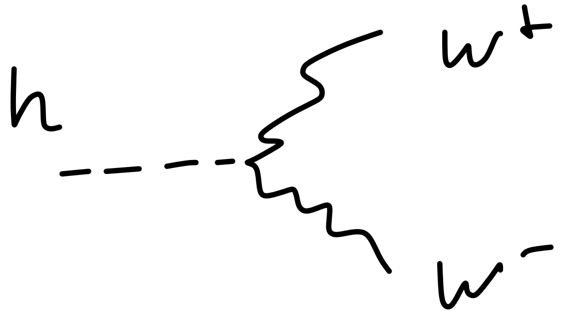
3 massive gauge vector bosons eat 3 d.o.f.

Unitary gauge: $\sigma = 0 = \phi^\pm$

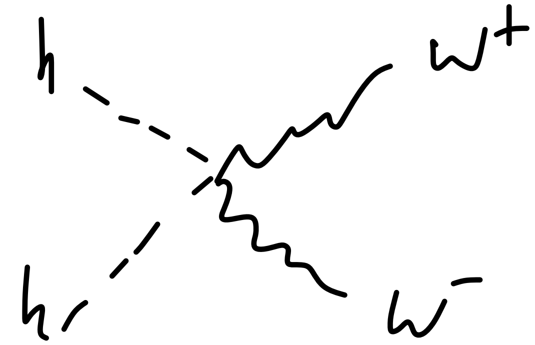
At high energy: $V_L \sim$ G. B.

Higgs gauge interactions

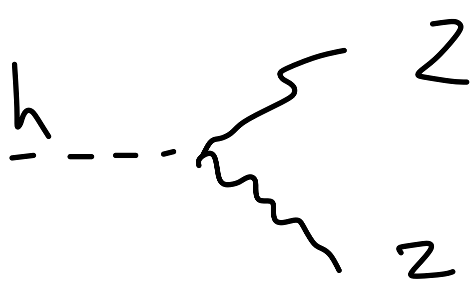
$$D_\mu \phi^\dagger D^\mu \phi \ni \frac{(v+h)^2}{v^2}\left(m_W^2 W^\mu W_\mu + \frac{m_Z^2}{2} Z_\mu Z^\mu\right)$$



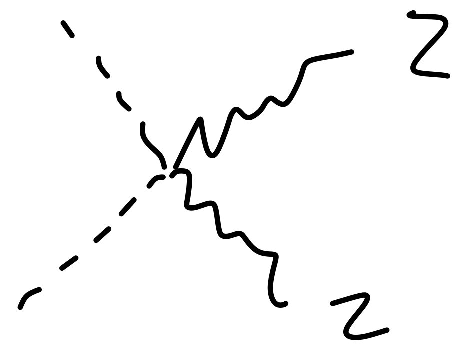
$\propto \frac{m_W^2}{v}\eta^{\mu\nu}$



$\propto \frac{m_W^2}{v^2}\eta^{\mu\nu}$

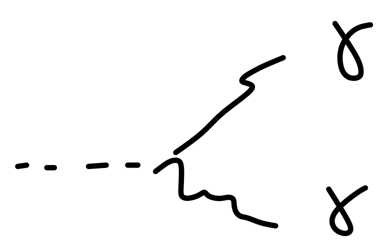


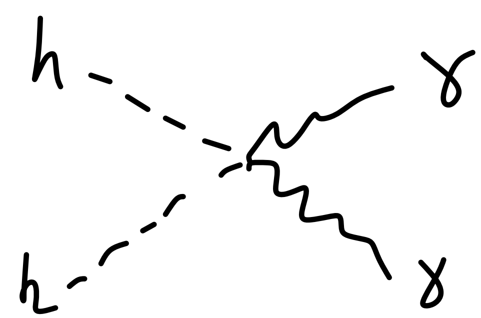
$\propto \frac{m_Z^2}{v}\eta^{\mu\nu}$



$\propto \frac{m_Z^2}{v^2}\eta^{\mu\nu}$

Again no

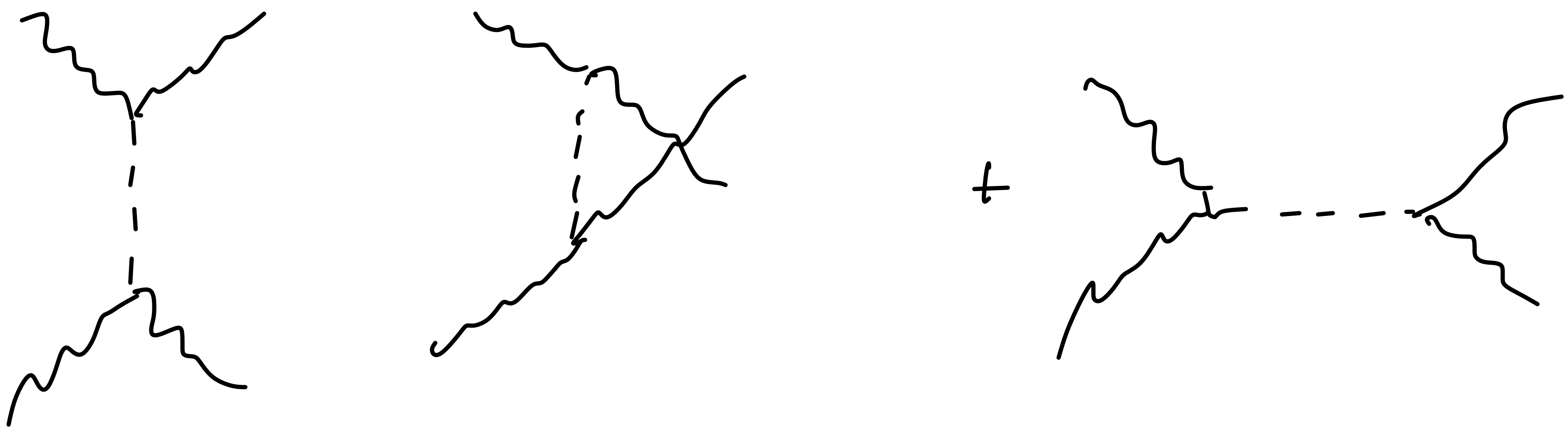




$Q(h) = 0$

C. Degrande

WW scattering



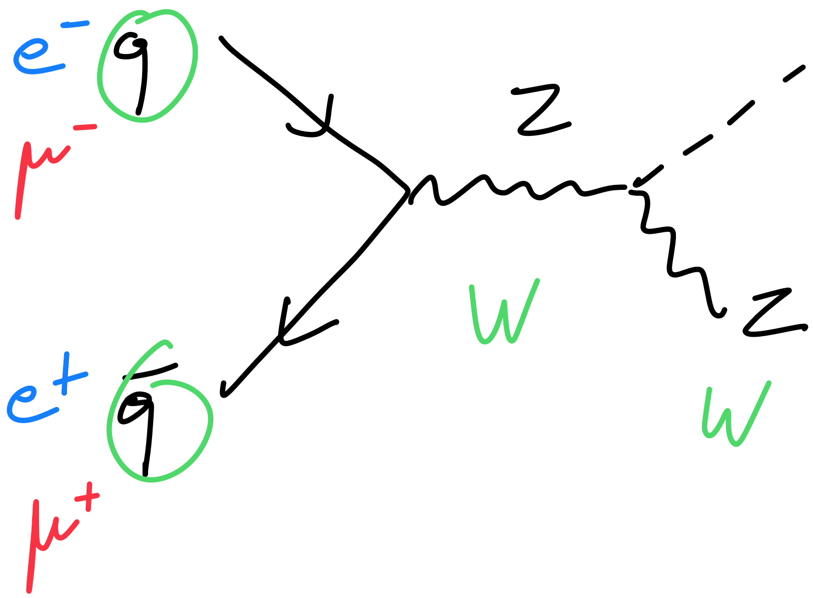
$$|M_4 + M_5|^2 \sim -\frac{g_2^2}{m_W^2}\left\{\frac{s^2}{s-m_h^2} + \frac{t^2}{t-m_h^2}\right\}$$

if $m_h << s, t \longrightarrow \sigma_{1+2+3+4+5} \sim \frac{1}{s}$

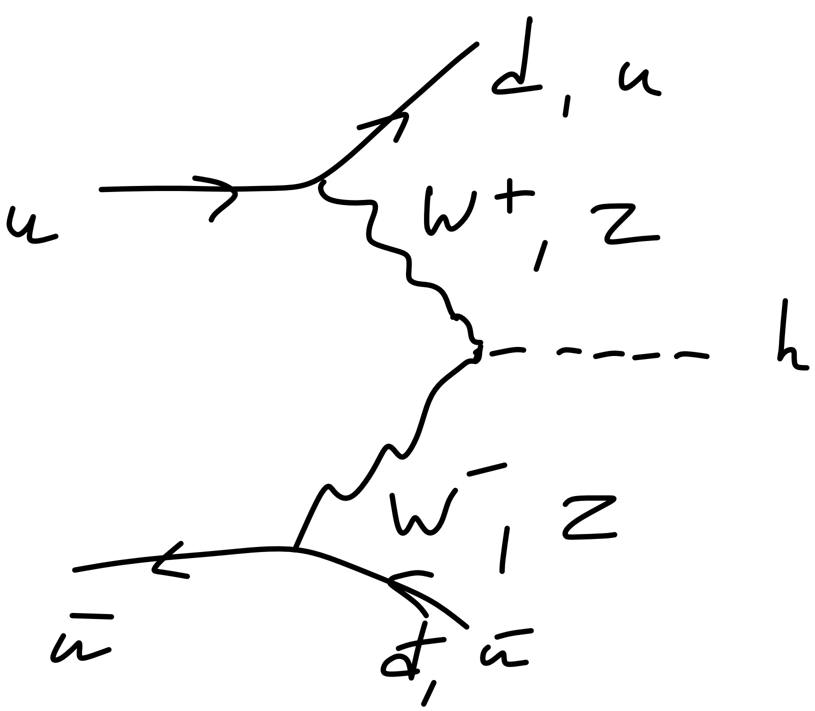
Test in MG
with & without
Higgs

No unitarity violation at high energy

Some H production



Associated production



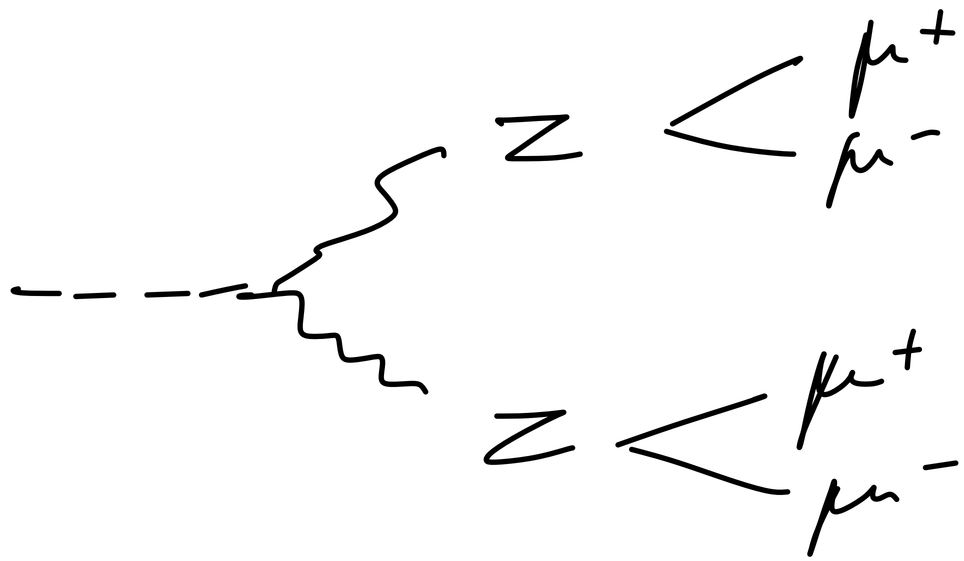
Vector boson fusion

C. Degrande

Some H decay

Depends on the Higgs mass

one off-shell



Golden channel

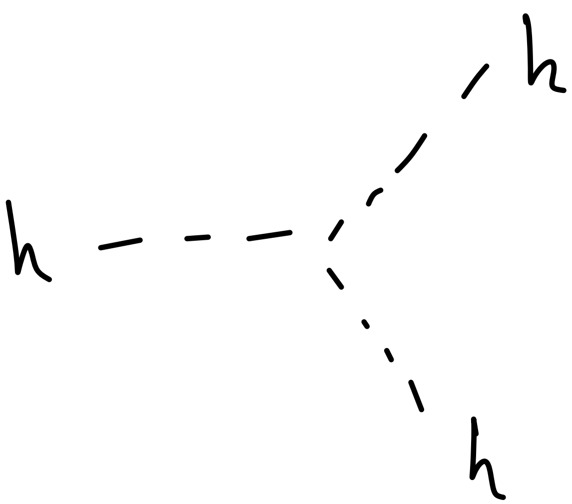
CMS

$2\lambda v = m_h^2$

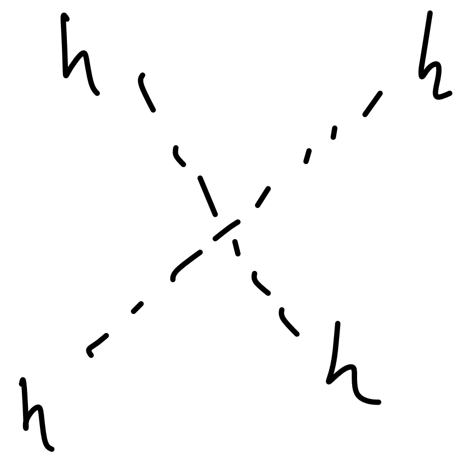
Free

Last free parameter

m_h or λ



$i\lambda v$

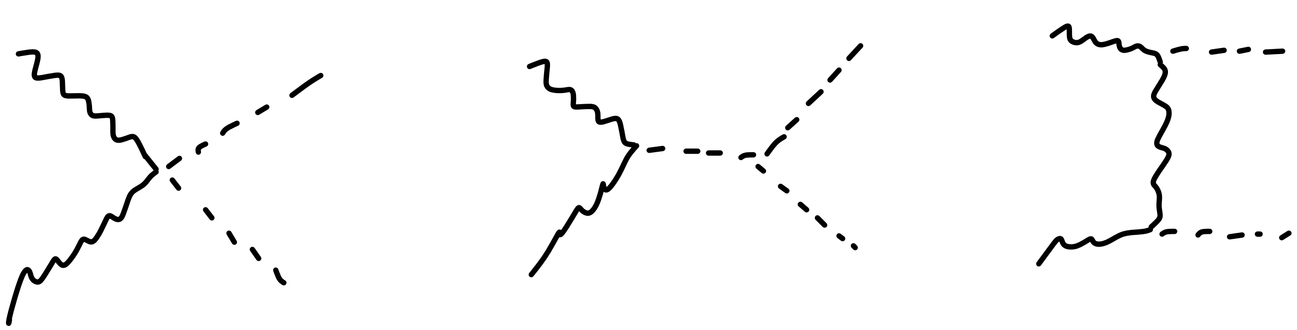


$i\lambda$

check the potential

consistency check

Double or more Higgs production but other diagrams



Fermion masses

$$m\bar\Psi\Psi = m(\underbrace{\bar\Psi_L \Psi_R}_{\bar L\, \ell_R} + \bar\Psi_R \Psi_L)$$

$\bar L$: $2_{SU(2)_L}$; ℓ_R: $1_{SU(2)_L}$

$\bar L\,\ell_R \rightarrow 2_{SU(2)_L}$, $Y = 1/2 - 1 = -1/2$

Same as ϕ

One field solve a problems!

not mass eigenstate

$$\mathcal{L}_{Leptons} = -y_e^{ij}\,\bar L'^i \phi\, \ell_R'^j + h.c. + i\bar L'^i \not{D} L'^i + i\bar\ell_R'^i \not{D} \ell_R'^i$$

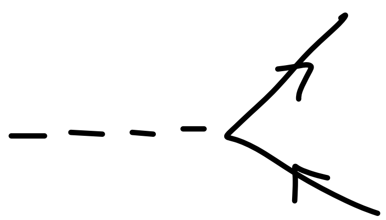
$$U_R\,\ell_R \equiv \ell_R' \qquad\qquad U_L L = L'$$

$$\mathcal{L}_{Leptons} = \underbrace{i\bar L \not{D} L + i\bar\ell_R \not{D} \ell_R}_{U_L,\,U_R \text{ disappear}} - \underbrace{\bar L \begin{pmatrix} y_e & & \\ & y_\mu & \\ & & y_\tau \end{pmatrix} \phi\, \ell_R}_{\bar\ell_L^i \frac{(v+h)}{\sqrt2} y_i\, \ell_R^i} + h.c.$$

U_L, U_R disappear

C. Degrande

More about lepton masses



$\frac{i m_\ell}{v}$

y^{ij} $\ni$ 18 parameters but only 3 are physical

Fermions $\propto$ m_F

Gauge bosons $\propto$ m_V^2

Quark masses

$$\mathcal{L}_{quarks} = i\,\bar{Q}'\not{D}Q' + i\,\bar{u}_R'\not{D}u_R' + i\,\bar{d}_R'\not{D}d_R'$$
$$- y_u^{ij}\,\bar{Q}'\tilde{\phi}\,u_R' - y_d^{ij}\,\bar{Q}'\phi\,d_R' + h.c.$$

$$U_R^u\,u_R = u_R' \qquad U_R^d\,d_R = d_R'$$
$$U_L^u\,u_L = u_L' \qquad U_L^d\,d_L = d_L'$$

No one for the left-handed but 2

$$\bar{u}_L'\,W^+\,d_L' \longrightarrow \bar{u}_L\,V_{CKM}\,W^+\,d_L$$

$$V_{CKM} \equiv U_L^{u\dagger}\,U_L^d$$ Unitary

$$d^j_{L/R} \longrightarrow e^{i\varphi_j^d}\,d^j_{L/R}\,,\quad u^j_{L/R} \longrightarrow e^{i\varphi_j^u}\,u^j_{L/R}$$

$V_{CKM} \ni$ 3 angles and one phase

Parameter counting

5 $g_1 \quad g_2 \quad g_3 \quad v \quad \lambda \quad \longleftrightarrow \quad \alpha_{EM} \quad G_F \quad M_Z \quad \alpha_s \quad m_h$

3 $y_e \,,\, y_\mu \,,\, y_\tau \quad \longleftrightarrow \quad m_e \,,\, m_\mu \,,\, m_\tau$

3 $y_d \,,\, y_s \,,\, y_b \quad \longleftrightarrow \quad m_d \,,\, m_s \,,\, m_b$

3 $y_u \,,\, y_c \,,\, y_t \quad \longleftrightarrow \quad m_u \,,\, m_c \,,\, m_t$

4 $V_{CKM} : \alpha, \beta, \gamma, \varphi \rightarrow \cancel{CP}$

18

Mostly from the Yukawa matrices!

3 generations

C. Degrande

Higgs production through top

$y_t \sim 1$ $\qquad$ $y_b \sim y_\tau \sim y_c \sim 10^{-2}$

$y_s \sim y_\mu \sim 10^{-3}$

$y_e \sim y_u \sim y_d \sim 10^{-5} \longrightarrow$ No $e^+e^-, u\bar{u}, d\bar{d} \to h$

too small

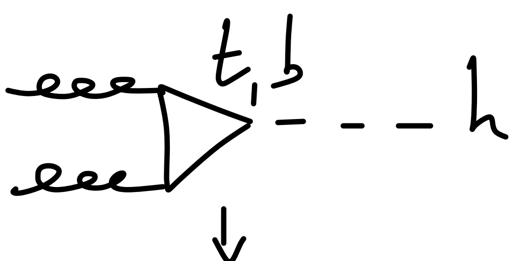
$m_p > m_n$

$\Uparrow$

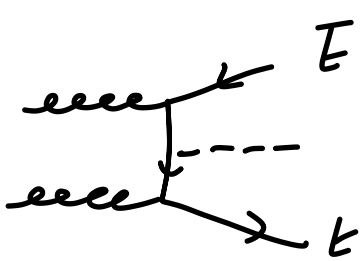
$y_u < y_d$

inverted!

$\Rightarrow$

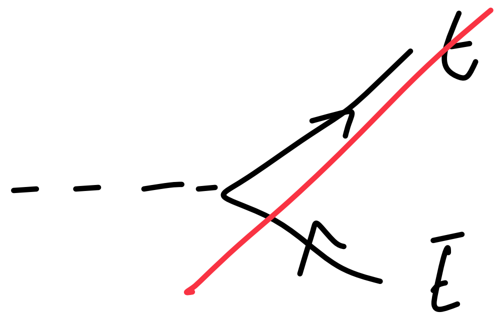


- loop induced but strong coupling and PDF
- top - bottom loop interference $\sim 5\%$

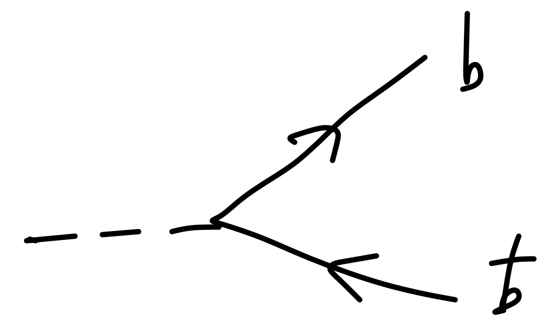


–

Higgs with fermions



too heavy



Largest but QCD background

$h \to \tau\,\bar{\tau}$, $h \to c\,\bar{c}$

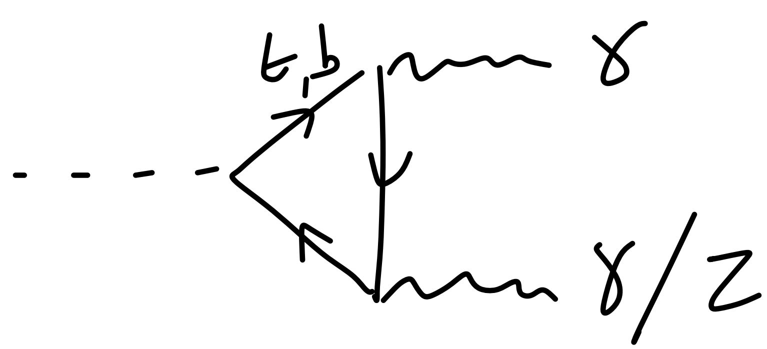
$\downarrow$

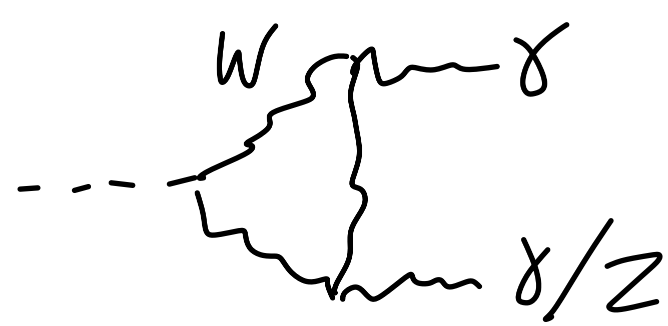
τ decay

charm tagging ?

$h \to \mu\,\mu$ 2500 smaller than

Loop induced





C. Degrande

Higgs exercises

$\sigma_{LHC}(pp \to h)$ with top, bottom & interference

$\sigma_{LHC}(pp \to Zh)$

$\sigma_{LHC}(pp \to W^{\pm}h)$

$\sigma_{LHC}(pp \to hjj)$

$\sigma_{LHC}(pp \to ht\bar{t})$

$\Gamma(h \to \gamma\gamma)$ with top, W & interference